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A Radical Method for Calculating Muzzle Motion From Proximity Sensor Data

by Ilmars Celmins

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14. ABSTRACT
A new method to process muzzle displacement transducer data has been developed and demonstrated on 5.56 and 40 mm weapon systems. The method allows much more flexibility in the placement of the measurement probes in a test fixture with no loss in measurement fidelity. The method also allows measurements to be taken with as few as two probes per axial measurement location, whereas previously used techniques required four probes.

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1. Introduction

An important component of accuracy or jump testing is the measurement of the muzzle motion. The motion of the gun tube is typically measured using inductive proximity probes (eddy probes) located near the muzzle. The eddy probes, when coupled with the appropriate drivers, generate an output voltage proportional to the gap between the probe and a conductive surface. When four probes are arranged at 90° intervals along the circumference of a gun tube, the four individual gap measurements can be combined to calculate the location of the center of the gun tube as discussed in Bornstein et al.[1] and Bornstein and Haug.[2]

Using two sets of eddy probes offset along the gun axis results in two bore centerline measurements. The difference between these measurements can be used to calculate the instantaneous muzzle-pointing angle. An extrapolation from the two measurements to the muzzle yields the lateral muzzle position. The time rate of change in lateral muzzle position is the muzzle-crossing velocity. The muzzle-crossing velocity ratio is a vector that is calculated by taking the arctangent of the ratio of the gun muzzle transverse velocity at the instant of shot exit to the projectile exit velocity. The muzzle-pointing angle and crossing velocity ratio are important quantities that define weapon contributions to accuracy and projectile jump.

During testing of the 40 mm M203 launcher firing the M433 projectile, it was found that the muzzle motion was larger than the measurement range of the standard eddy probes as described by Celmins and Guidos.[3] This report describes the modifications that were implemented to overcome these limitations.

The net result of the modifications is that a more robust and flexible muzzle measurement technique has been developed.

[1]Bornstein, J. A.; Celmins, I.; Plostins, P.; Schmidt, E. M. *Techniques for the Measurement of Tank Cannon Jump*; BRL-MR-3715; U.S. Army Ballistic Research Laboratory: Aberdeen Proving Ground, MD, December 1988.

[2]Bornstein, J. A.; Haug, B. T. *Gun Dynamics Measurements for Tank Gun Systems*; BRL-MR-3688; U.S. Army Ballistic Research Laboratory: Aberdeen Proving Ground, MD, July 1988.

[3]Celmins, I.; Guidos, B. J. *Accuracy and Jump Measurements of the 40-mm M203 Launcher Firing the M433 Projectile*; ARL-TR-4602; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, September 2008.

2. Previously Used Measurement Technique

2.1 Probe Locations and Algorithm

The use of proximity probes to measure gun tube motion was originally developed for large caliber (tank gun) accuracy testing. These techniques were scaled down and successfully used for small caliber accuracy testing as described by Celmins.[4]

The standard eddy probe configuration for these tests was to use two sets of four probes each, attached to a fixed mount (not connected to the barrel). Figure 1 shows a typical eddy probe fixture. When four probes are arranged at 90° intervals along the circumference of a gun tube, the four individual gap measurements can be combined to calculate the location of the center of the gun tube at this location as discussed in Bornstein et al.[1] and Bornstein and Haug.[2] The center location is calculated in two planes by taking the difference in gap measurements from two opposing probes, adjusted by initial preshot gap measurements used as offsets for the calculation. Using two sets of eddy probes offset along the gun axis results in two bore centerline measurements. The difference between these measurements can be used to calculate the instantaneous local muzzle-pointing angle. An extrapolation from the two measurements to the muzzle yields the muzzle position (assuming minimal bore curvature from the probes to the muzzle). The time rate of change in muzzle position is the muzzle-crossing velocity.

An advantage of this differential measurement system is that it is independent of the gun tube external diameter. As long as the gaps between the gun tube and the eddy probes remain within the measurement range of the probes, then the differential measurement will indicate the center of the bore. The measurement will not be affected by tube expansion or barrel taper on a recoiling barrel, because either of these effects would affect each gap equally.

[4]Celmins, I. *Jump Component Measurement Methodology for Small-Caliber, Spin-Stabilized Ammunition*; ARL-TR-4259; U.S. Army Research Laboratory: Aberdeen proving Ground, MD, September 2007.

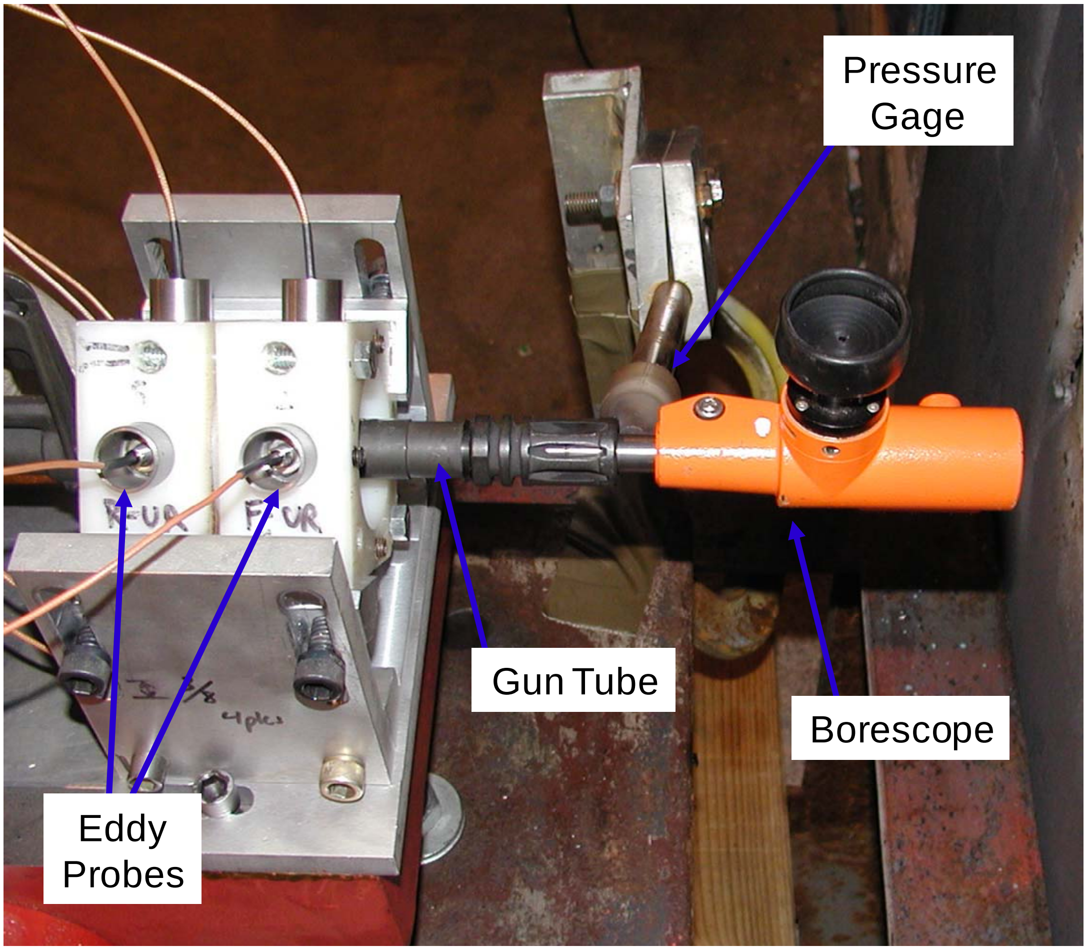

Figure 1. Gun muzzle, borescope, and eddy probes.

2.2 Limitations of the Traditional Measurement Methodology

Several problems were identified with the traditional measurement methodology. The first of these was discussed in Celmins.[4] It was found that when the eddy probes were equally spaced around the circumference of a 5.56 mm gun barrel, there was electrical interference between probes due to their close proximity to each other. This was solved by partially shielding the probes and modifying the analysis software to account for the resulting nonlinearities in the probe calibrations. An undesirable side effect of the shielding was to effectively cut the measurement range of the probes in half. This reduced measurement range was not a problem with the 5.56 mm system due to the small amount of barrel motion.

More serious problems were discovered when testing a 40 mm M203 grenade launcher. These tests are described in Celmins and Guidos[3] and also in the sample measurements section of this report. The most serious problem was that the M203 barrel motion was on the order of 3 mm, which would necessitate an eddy probe measurement range of 6 mm if the probes are mounted

opposite each other and initially centered in their measurement range. The standard measurement range of the eddy probes is only 2.54 mm, and the range was further reduced to 1 mm for the aluminum M203 tube.

3. Radical New Approach

3.1 Radical Lines

Several of the algorithms to be discussed utilize the concept of a "radical line" or "radical axis," so a brief description of this geometric construct is warranted.

From Wikipedia (http://en.wikipedia.org/wiki/Radical_axis):

> "The radical axis of two circles is the locus of points at which tangents drawn to both circles have the same length. …The radical axis is always a straight line and always perpendicular to the line connecting the centers of the circles, albeit closer to the circumference of the larger circle. If the circles intersect, the radical axis is the line passing through the intersection points; similarly, if the circles are tangent, the radical axis is simply the common tangent."

This is more easily understood by examining the examples of radical lines shown in figure 2.

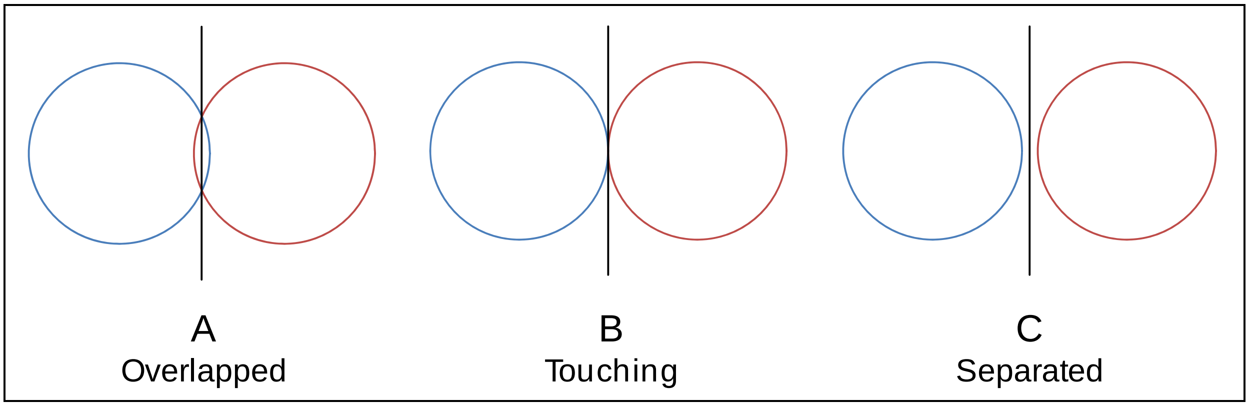

Figure 2. Examples of circles with radical lines.

For two circles having centers at (a_1, b_1) and (a_2, b_2) and radii of r_1 and r_2, the equation of the radical line is

$$2(a_1 - a_2)x + 2(b_1 - b_2)y + c = 0, \tag{1}$$

where

$$c = a_2^2 - a_1^2 + b_2^2 - b_1^2 + r_1^2 - r_2^2. \tag{2}$$

3.2 Radial Measurements

Previous eddy probe processing used differential gap measurements on opposing probes to calculate bore center displacements. The new techniques use a combination of the gap and the barrel outside diameter to calculate a radial distance from the probe to the center of the barrel. These radial measurements are then used in various ways to calculate the bore center location. One thing that is immediately obvious is that radial measurements will be inaccurate if the barrel diameter is not correct, either due to measurement error, taper on a recoiling barrel, or barrel expansion due to pressure. This will affect different techniques to different degrees, and its effect will be discussed for each technique.

These methods also require that the initial probe locations are known, both in distance and angle. The angular orientation of the probes is determined by the probe holding fixture. Because the fixture is usually a precisely machined part, the probe orientation in the fixture is known very accurately.

The initial radial position of each probe is determined by taking a static reading of the gun barrel. This reading provides the magnitude of the gap between the probe and the barrel surface. The probe radial position is found by adding the measured gap to the known radius of the gun barrel. This method assumes the barrel is initially centered in the fixture. In practice, the barrel is positioned close to the fixture center and then the static readings are taken. The barrel center then becomes the origin of the coordinate system used for barrel displacement measurements. If the barrel is not exactly centered in the fixture, then a small error is introduced in the assumed angular orientation of the probes relative to the center. Fortunately, the net effect of this error is insignificant for small barrel displacements because position is measured relative to the starting point, not as an absolute location.

3.3 Four Probes

The first technique to be discussed uses the standard configuration of two sets of opposing probes but processes the data using radial distance and radical line calculations instead of differential gap measurements. When a probe reading is taken, the center of the barrel should be located at the calculated radial distance from the probe (barrel radius + probe gap). If there are no measurement errors and the barrel is not offset perpendicular to the probes, then two radial distances from two opposing probes should intersect at a single point, as in two circles touching, shown in figure 2b. In reality, the conditions illustrated in figures 2a and 2c are more likely—the radii will either intersect or not meet. In any of these three cases, the radical line between the opposing gage radial circles will pass through the barrel center. When radical lines are calculated from two different (e.g., orthogonal) probe pairs, then the intersection point of the two radical lines will uniquely define the center of the barrel.

One advantage of this technique is that the probe locations are completely arbitrary. The algorithm just needs to know the angular positions of the four probes. The probe pairs can be at any angle to accommodate barrel or test fixture features. The two probe pairs do not need to be orthogonal, although measurement accuracy in one plane will decrease as the angle between probe pairs becomes smaller. Opposing probes in a pair also do not need to be exactly opposite each other (a line between the probes does not need to pass through the center of the barrel). The algorithm still works regardless of the probe position. This is illustrated in figure 3.

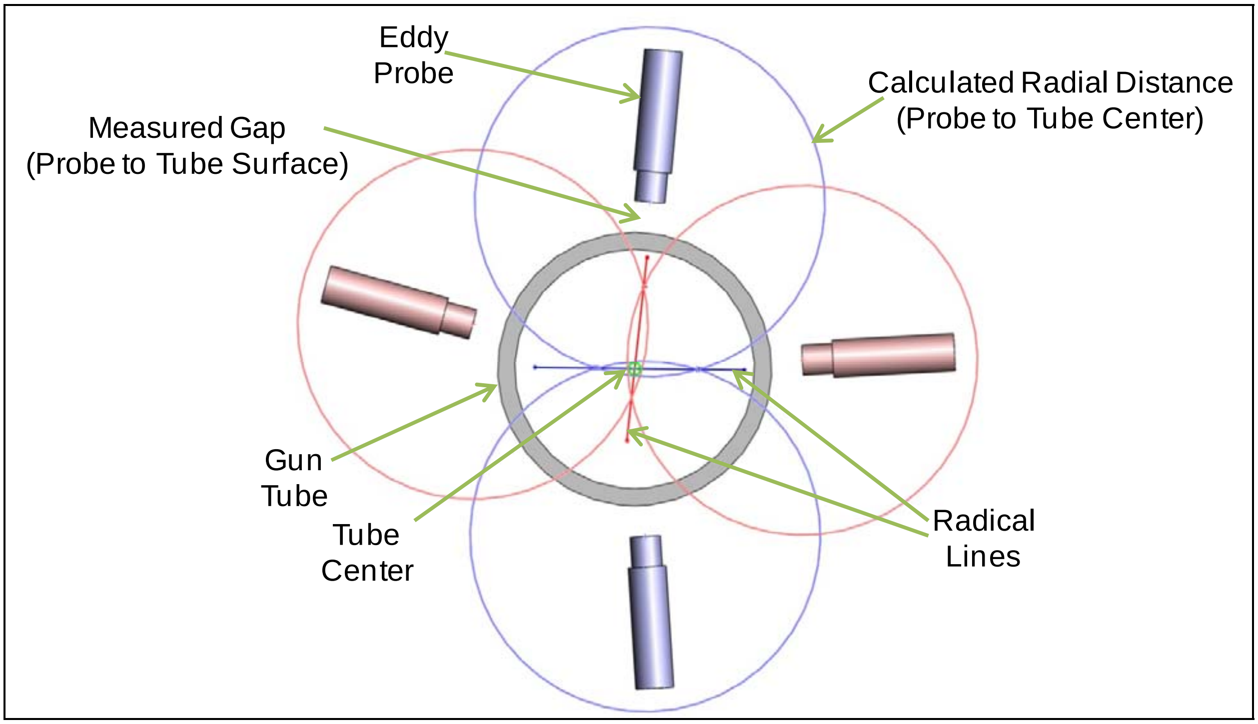

Figure 3. Illustration of four-probe measurement using radical lines.

The previously used gap-based system always assumed that probe pairs were orthogonal and positioned either horizontal and vertical or at a 45° orientation. Switching between these conditions required recoding the processing algorithms. When the measurement planes are orthogonal, the measurements are independent (e.g., horizontal and vertical). If the planes are not orthogonal, then a different processing methodology is needed, essentially calculating the intersection point of lines normal to the lines between gages and offset from the center by the differential gap. Describing this method in detail is not the purpose of this report. The bottom line is that the previously used methods and algorithms currently only accommodate orthogonal probe pairs.

Finally, the sensitivity to barrel diameter needs to be addressed. Figure 3 shows what would happen if the barrel diameter is smaller than expected, for example if a tapered gun tube had recoiled under the probes. As can be seen, the calculated radial distance for each probe extends

past the tube center, because the distance calculation uses the larger tube radius. However, because the same tube diameter error is applied to all four probes, there is no net error in the center calculation, and the radical lines still intersect at the center of the gun tube.

3.4 Three Probes

The radial distance calculation can also be easily applied to a system using three proximity probes instead of four. The radical axis theorem states that for three circles, the three radical axes (one for each pair of circles) intersect in one point called the radical center or are parallel. When three probes are used, the radical center is calculated and used as the center of the barrel as illustrated in figure 4. Because it is a mathematical requirement that all three radical lines must intersect at a single point, it is only necessary to find two of the radical lines and their intersection.

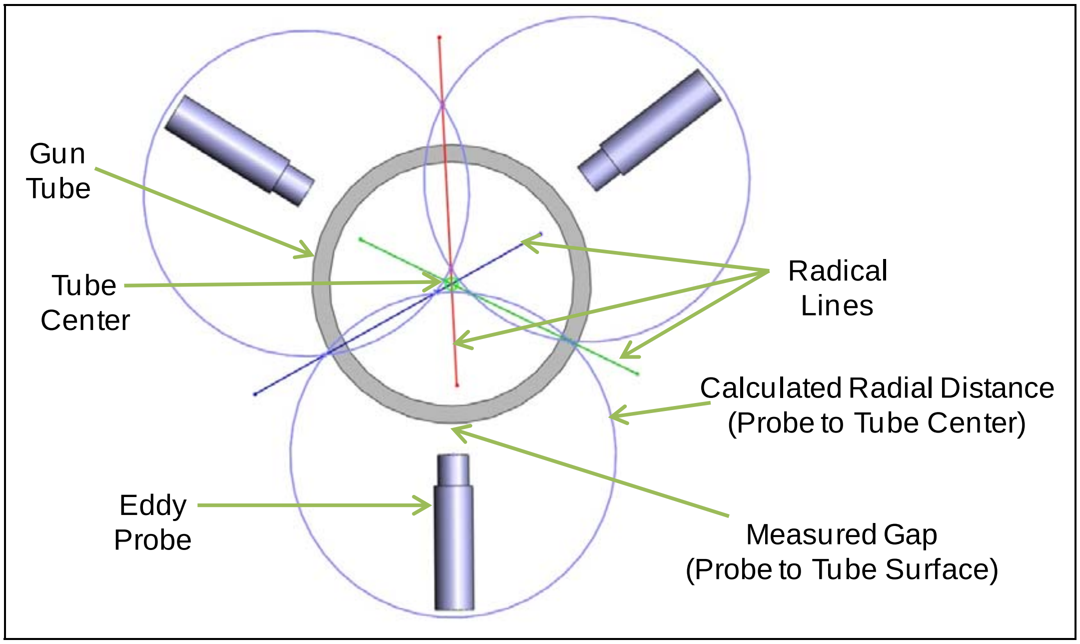

Figure 4. Illustration of three-probe measurement using radical lines.

The three-probe technique is also independent of probe location—theoretically the probes can be arranged anywhere around the circumference of the gun barrel. In reality, it is preferable to avoid putting two probes too close together, both to avoid electrical interference and because the centerline calculation would become more sensitive to measurement errors in the direction perpendicular to the two adjacent probes.

This method is also insensitive to barrel diameter variations. In figure 4, the effect of an oversized gun tube is illustrated, which could happen due to tube expansion. As a result, the calculated radial distances are all too small so that they do not reach the actual tube center. However, because the same tube diameter error is applied to all three probes, there is no net error in the center calculation, and the radical lines still intersect at the center of the gun tube.

3.5 Two Probes

The radial distance approach allows barrel motion to be determined using two probes but only under certain conditions. The technique is discussed first, followed by an explanation of the limitations.

There are two primary requirements for using two probes to get the tube center location. The first is that the probes must not be positioned opposite each other, that is, a line between the probes should not pass through the center of the tube. The second requirement is that the gun tube diameter must be precisely known and that it cannot change during the measurement interval. Therefore, this method is not suitable for tapered recoiling tubes or gun tubes that exhibit a significant amount of barrel expansion during firing.

Figure 5 illustrates how the two-probe measurement works. This method does not use radical lines. Instead, one of the intersection points between the radial distance circles from the two probes is used to determine the tube center. There will be two intersection points—the correct one is the point closest to (0, 0) in barrel coordinates. This is because the muzzle motion measurement origin is defined as the initial (preshot) tube center, and the barrel cannot move far from this initial location and still be within the measurement range of the probes. Additional information is needed to initially determine which point to use to establish the origin. For the situation illustrated in figure 5, the geometry dictates that the lower of the two points is the correct one.

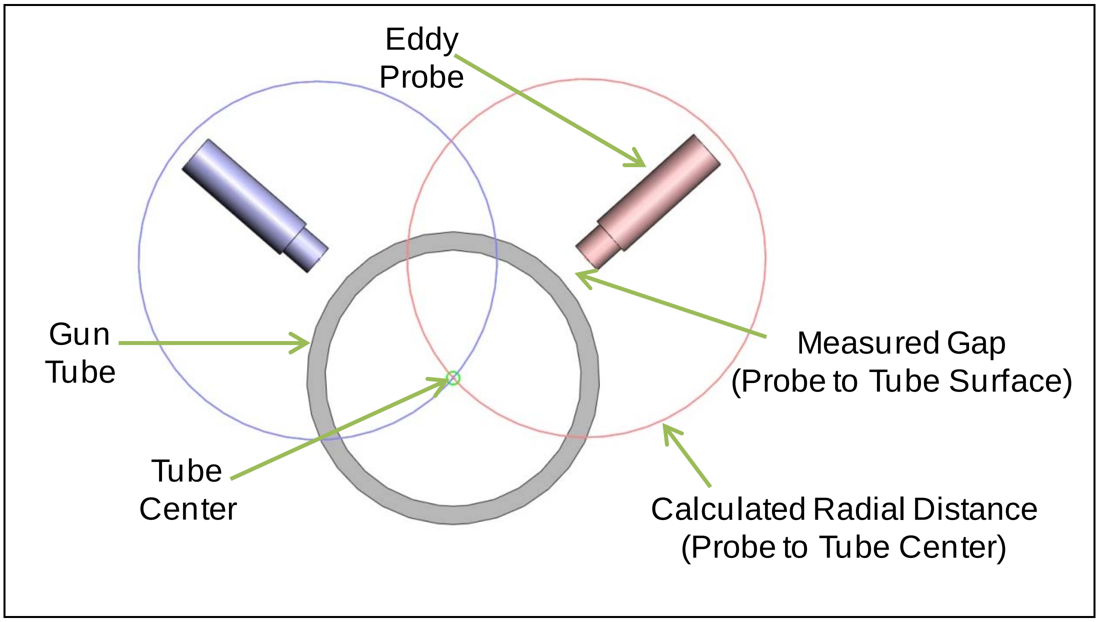

Figure 5. Illustration of two-probe measurement.

As stated previously, the two-probe method is extremely sensitive to tube diameter. For the probe configuration shown in figure 5, an increase in bore diameter would result in undersized radial distance calculations, which would manifest as an apparent upward displacement of the tube center along the radical line between the two probes (not shown).

The only time that this method should be used is when it is not feasible to use three or four probes, either due to electrical interference, barrel or weapon geometry, or other factors.

3.6 Weighted Averages

When three or more gages are present, then a weighted average technique can be used to calculate the tube center. For example, with three gages the following techniques can be used:

1. The radical center of the three probes.
2. Three separate two-probe measurements (1–2, 1–3, 2–3).
3. A hybrid system combining the radical line from two gages, intersected by the radial distance from the third gage. This would provide three additional measurements.

The reason a weighted average could be preferable to just using the previously described three-probe technique has to do with the details of the eddy probe signal. It was mentioned previously that shielding the probes resulted in a nonlinear displacement versus voltage profile. When the probes were used on the aluminum 40 mm M203 tube; this nonlinearity issue was exacerbated by amplifier modifications that were done to extend the measurement range. The nonlinear response results in probes being much more sensitive when the gap is small than they are for larger gaps.

Ideally, a weighted average gives extra weight to measurements that are within the more sensitive range of the probes and also gives more weight to center calculation techniques that utilize only the more sensitive probes. For example, if the barrel moves away from one probe and closer to the other two, then a two-probe measurement from the closer probes would be given more weight than the three-probe reading. The probes that are in the more sensitive region change over time as the barrel moves closer to some probes and farther from others, so the weighting needs to be recalculated at each time step.

4. Sample Measurements

Two sets of sample measurements are provided: one set shows comparisons between the new technique and the traditional one, and a second set shows sample measurements for the 40 mm test where the traditional system could not be used. The first set of sample measurements compares traditional differential gap measurements, four-probe radical line measurements, three-

probe radical line measurements, and two-probe radial measurements. The probes were positioned symmetrically around the barrel, midway between the horizontal and vertical planes as shown in figure 1. The axial front and rear locations were 64 and 106 mm, respectively, from the muzzle. The weapon under test was an M4 rifle, and the ammunition fired was a 5.56 mm M855.

All of these measurements started with the same raw eddy probe data. For the three-probe and two-probe measurements, data from one or two probes was discarded at both the front and rear locations. Figures 6 and 7 show barrel centerline horizontal and vertical displacements at the rear and front gage locations for all four processing methods. The measurements in the top left figures were generated by processing the data via differential gap measurements. The top right figures show data processed using the radical line method using measurements from all four probes. The data in the bottom left figures was processed using only three of the probes at each location, and the bottom right figures used two probes.

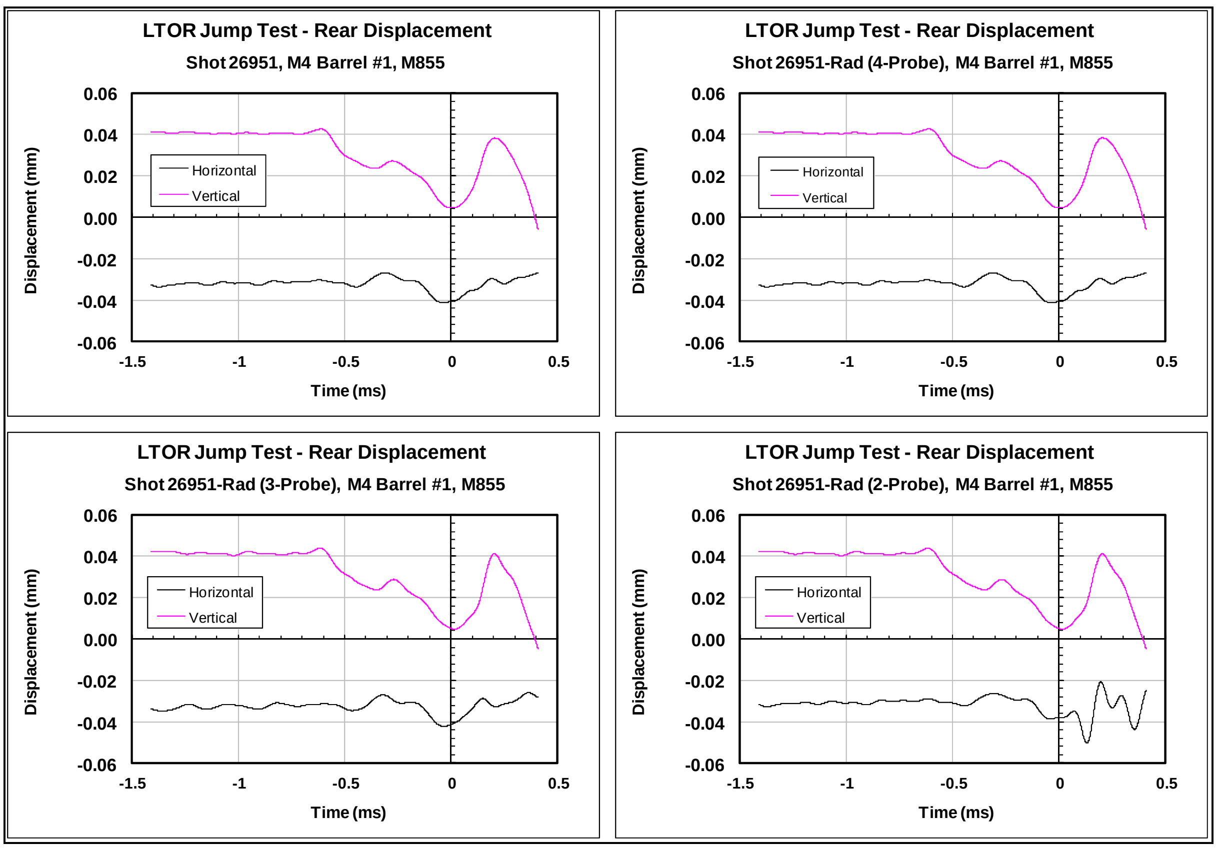

Figure 6. Barrel displacement at rear probe location: traditional four-probe gap (top left), four-probe radical (top right), three-probe radical (bottom left), and two-probe (bottom right).

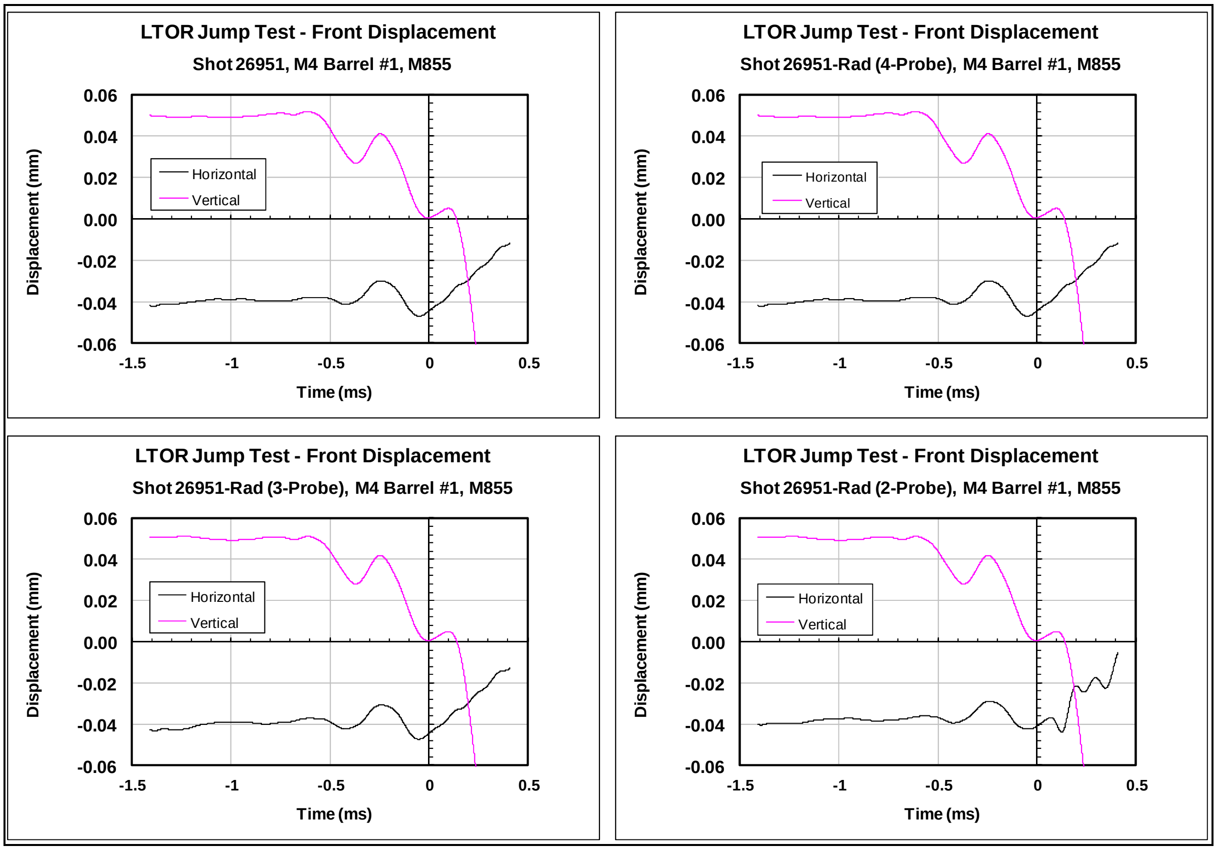

Figure 7. Barrel displacement at front probe location: traditional four-probe gap (top left), four-probe radical (top right), three-probe radical (bottom left), and two-probe (bottom right).

Comparison of the top figures shows that there is virtually no difference in the calculated barrel center locations for the traditional and radical approaches when data from all four probes is used. This serves as confirmation that the algorithm is implemented properly.

The bottom figures show calculated barrel centers when using radical lines from three probes or intersecting circle measurements from two probes. There are some data differences from the other methods.

Figure 8 shows calculated muzzle-pointing angle for the same four methods. The pointing angle is calculated by taking the arctangent of the difference in the front and rear barrel centers at each point in time divided by the probe separation. It is expected that pointing angle data will exhibit more discrepancies between methods, because this is a differential calculation, and indeed this is the case when comparing the three-probe and two-probe measurements with the other two techniques. However, this difference is typically on the order of several 100ths of a milliradian. The only alternative when using the previous differential gap technique was to not have any muzzle motion data when measurements from a single probe were lost.

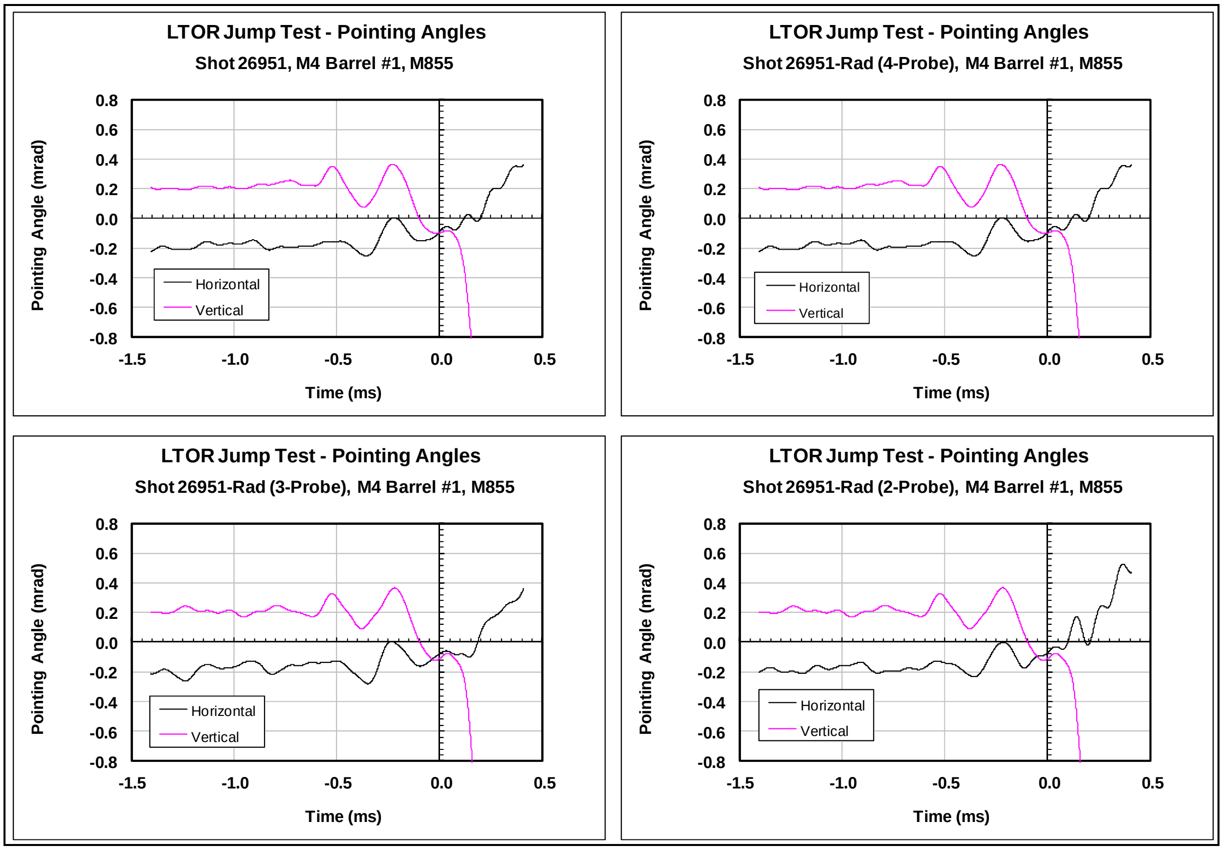

Figure 8. Barrel-pointing angle: traditional four-probe gap (top left), four-probe radical (top right), three-probe radical (bottom left), and two-probe (bottom right).

Figure 9 shows calculated muzzle- crossing velocity for the same four methods. Crossing velocity is calculated by extending a line through the rear and front calculated barrel positions to the axial location of the muzzle (to get muzzle location), and then calculating the time rate of change of this location to get muzzle-crossing velocity. Essentially, this parameter is calculated from the pointing angle combined with a displacement measurement, so the differences between measurement techniques are similar to those seen for the muzzle-pointing angle data.

Figure 10 shows the muzzle-pointing angles overplotted on a single graph in order to highlight differences between the measurement techniques. It is difficult to distinguish the two sets of four-probe measurement traces, because they are virtually identical. Also, for the vertical measurements, the two-probe and three-probe traces are overlapped. The reason for this has to do with which probes were utilized. For the three-probe measurements, the bottom left probe was removed. For the two-probe measurements, both the bottom left and upper left probes were eliminated, leaving the upper right and lower right probes. These two remaining probes were 45° above and below horizontal, respectively. This means the two radial circle intersection points for these probes would lie in a nominally horizontal line. By definition, the radical line between the two radial circles passes through these two intersection points. This same radical line is used to

calculate the three-probe center, so the calculated vertical center point for the two methods is coincident. The two-probe horizontal readings start to deviate significantly after time = 0. Shot exit for this test configuration occurred at approximately –0.039 ms. For accuracy testing, we are usually only concerned with pointing angle prior to shot exit, because what the barrel does after the bullet has left does not affect the trajectory.

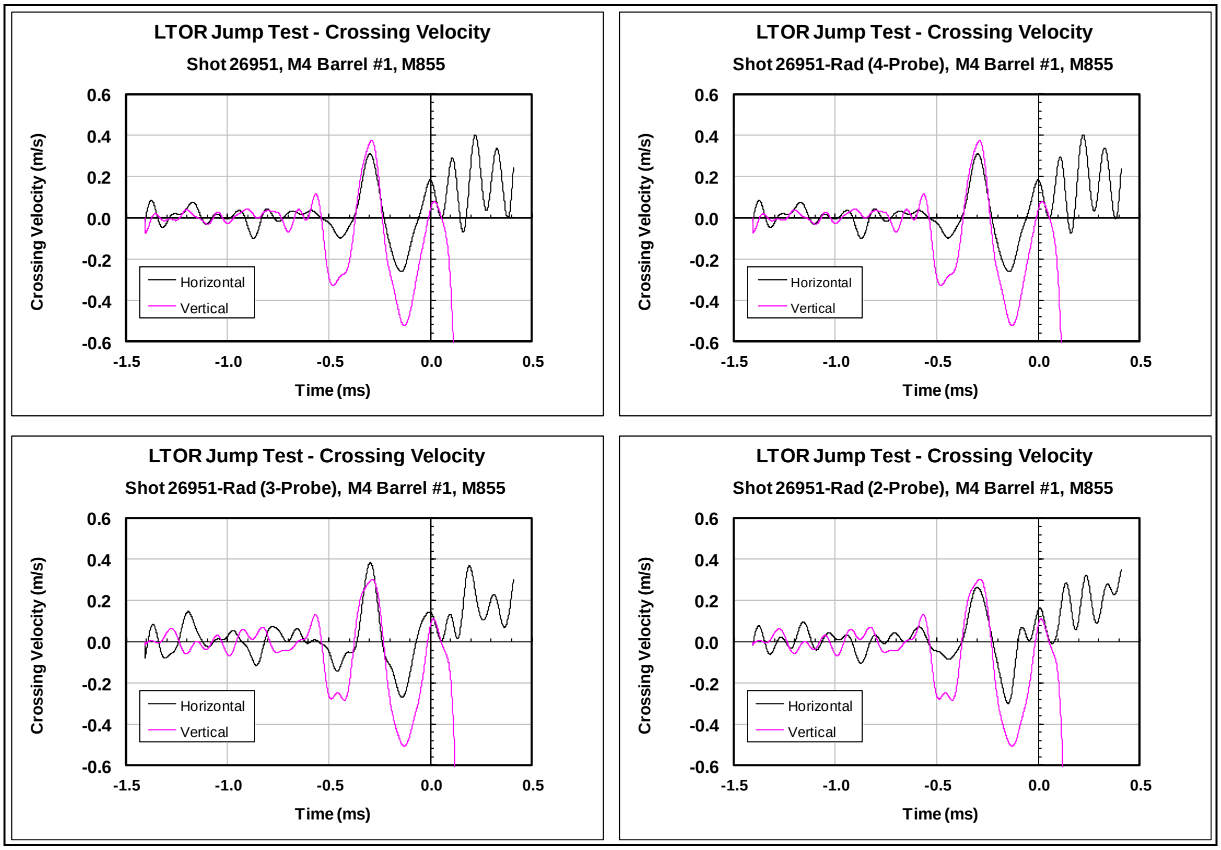

Figure 9. Barrel-crossing velocity: traditional four-probe gap (top left), four-probe radical (top right), three-probe radical (bottom left), and two-probe (bottom right).

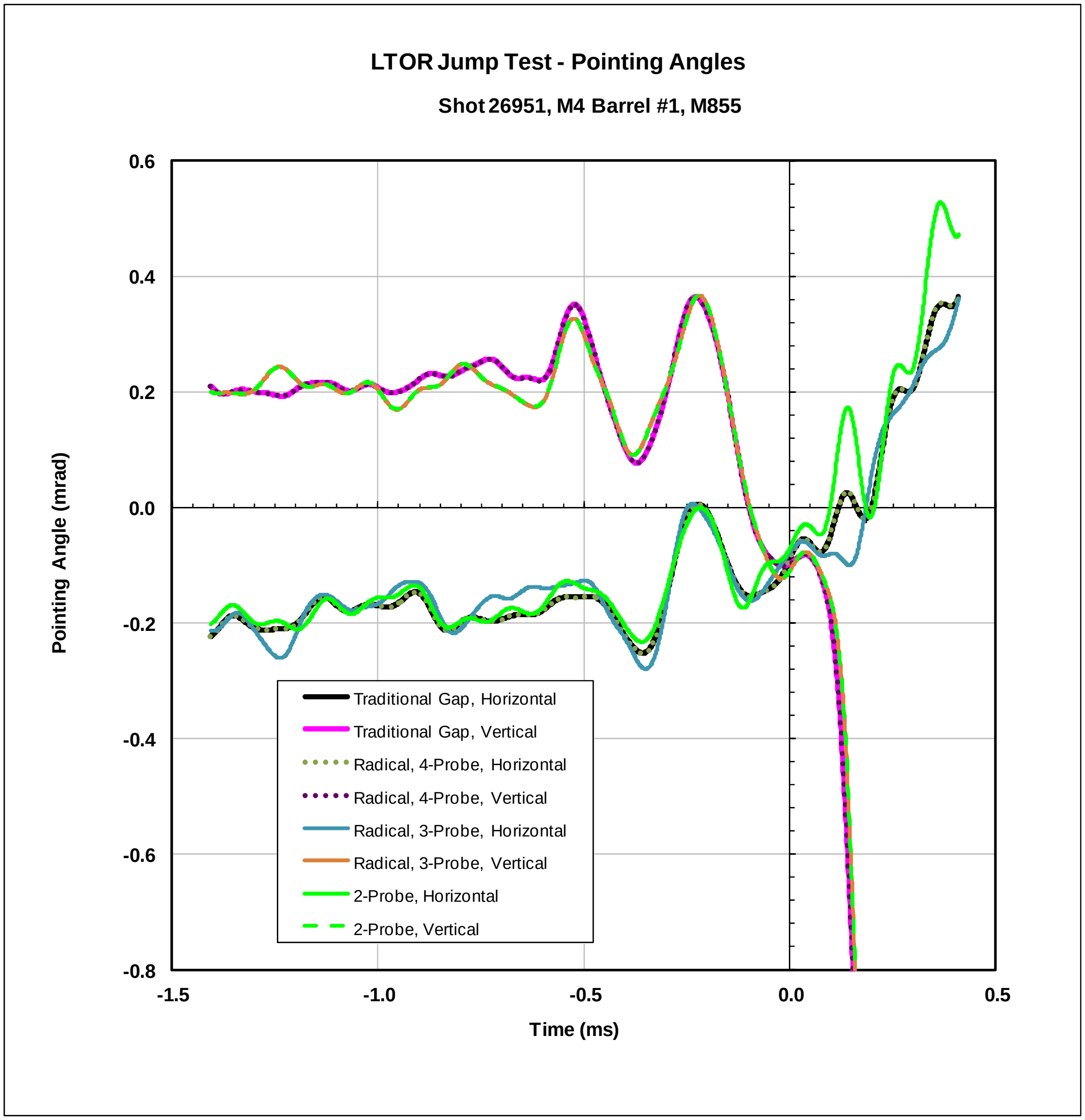

Figure 10. Overplotted barrel-pointing angle.

The second set of sample measurements were taken during testing of the 40 mm M203 launcher firing the M433 projectile as described by Celmins and Guidos.[3] The test setup is shown in figure 11. The 40 mm M203 launcher is attached underneath the 5.56 mm rifle barrel. This test setup utilized two sets of three eddy probes (front and rear). At each location, the three probes were oriented approximately 120° apart, offset approximately 60° circumferentially between the front and rear probe sets. This probe arrangement resulted in the maximum separation between probes and, thus, minimized electrical interference. The probes could not be positioned at precisely even spacing due to mechanical interference with the test fixture.

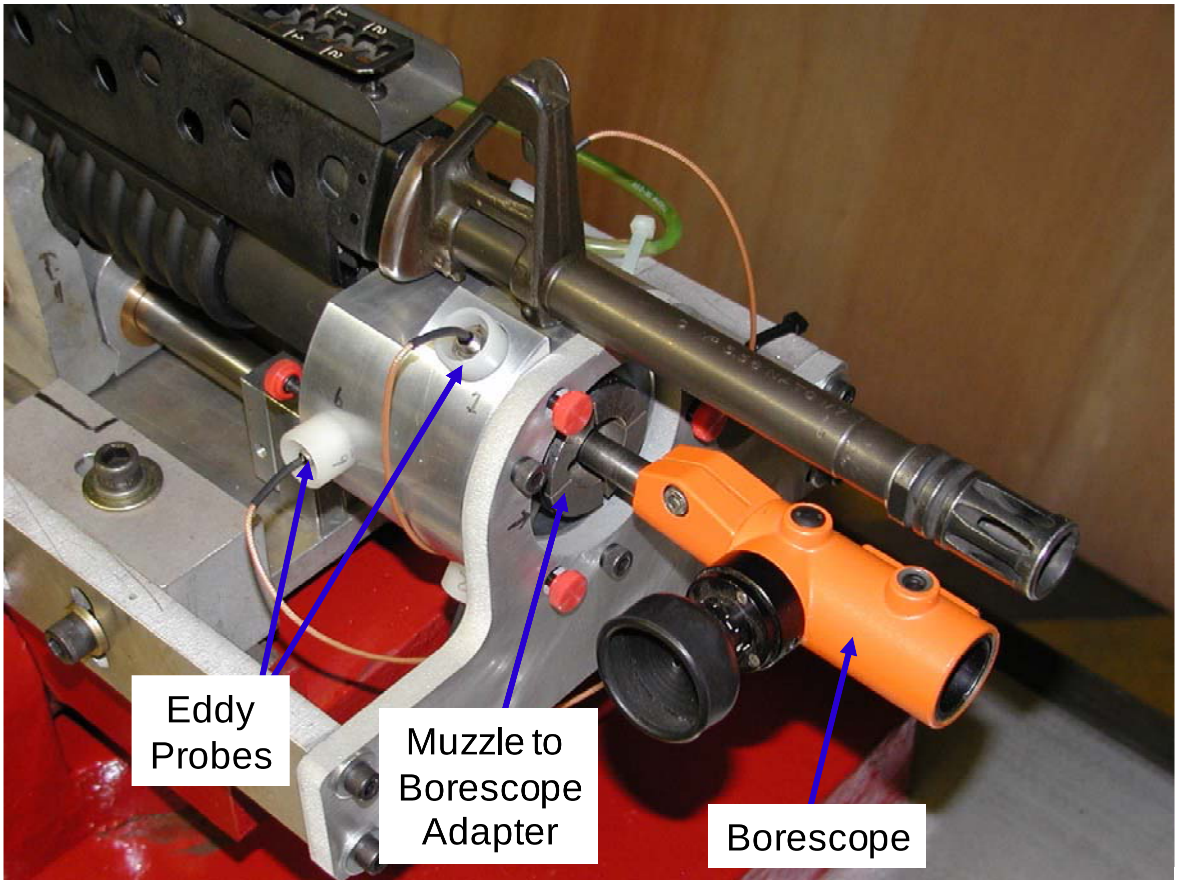

Figure 11. 40 mm test configuration.

For the 40 mm testing, several problems required resolution when using the eddy probes:

1. The eddy probes were designed to be used with steel. The M203 launcher has an aluminum barrel. It was discovered the eddy probe measurement range was reduced by 60% from 2.54 mm (0.1 in) to 1 mm when sensing aluminum.

2. Preliminary testing showed that the muzzle motion for the M203 launcher was on the order of 3 mm. In the standard mounting configuration where probes are positioned on opposite sides of the barrel and initially centered in their measurement range, 3 mm of barrel motion would require a 6 mm minimum measurement range for each probe.

3. Additionally, when the eddy probes were mounted in a standard configuration where they were spaced at 90° increments around the circumference of the barrel, there was electrical interference between the probes due to their close proximity to each other. This issue was addressed in Celmins,[4] but the solution that was used further reduced the measurement range by a factor of 2. This was not practical for the 40 mm testing, because measurement range was inadequate to start with.

The radical line measurement technique was initially developed to address these issues.

Figure 12 shows the calculated barrel displacement for a typical 40 mm shot. As can be seen, the maximum displacement is near 3 mm, which is three times the normal measurement range of a single probe with an aluminum barrel. This large barrel motion was addressed in two ways: (1) the eddy probe amplifiers were physically modified to extend the measurement range so that useful readings could be attained at 6 mm gaps, albeit at a significantly reduced resolution; and (2) the weighted average measurement technique was implemented to utilize readings within the more accurate range of the probes. The resultant calculated pointing angle is shown in figure 13, and crossing velocity is shown in figure 14.

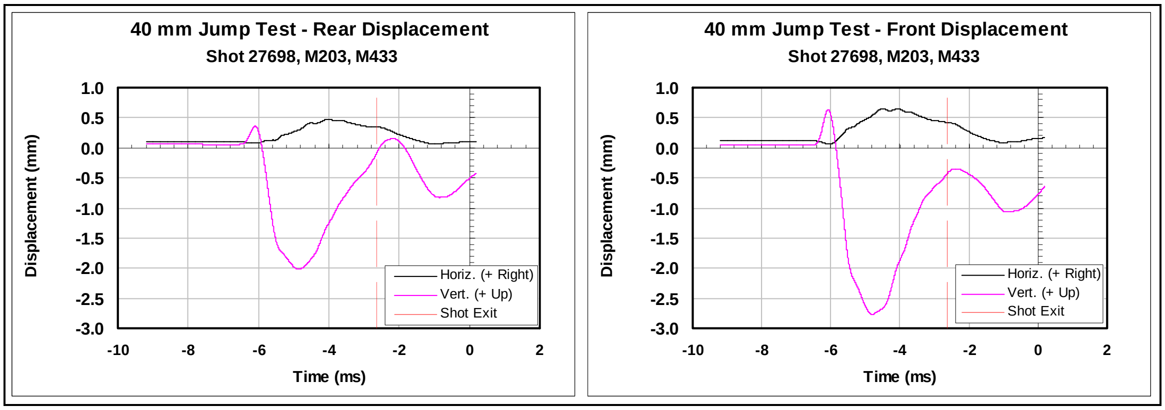

Figure 12. Barrel displacement at rear and front measurement locations.

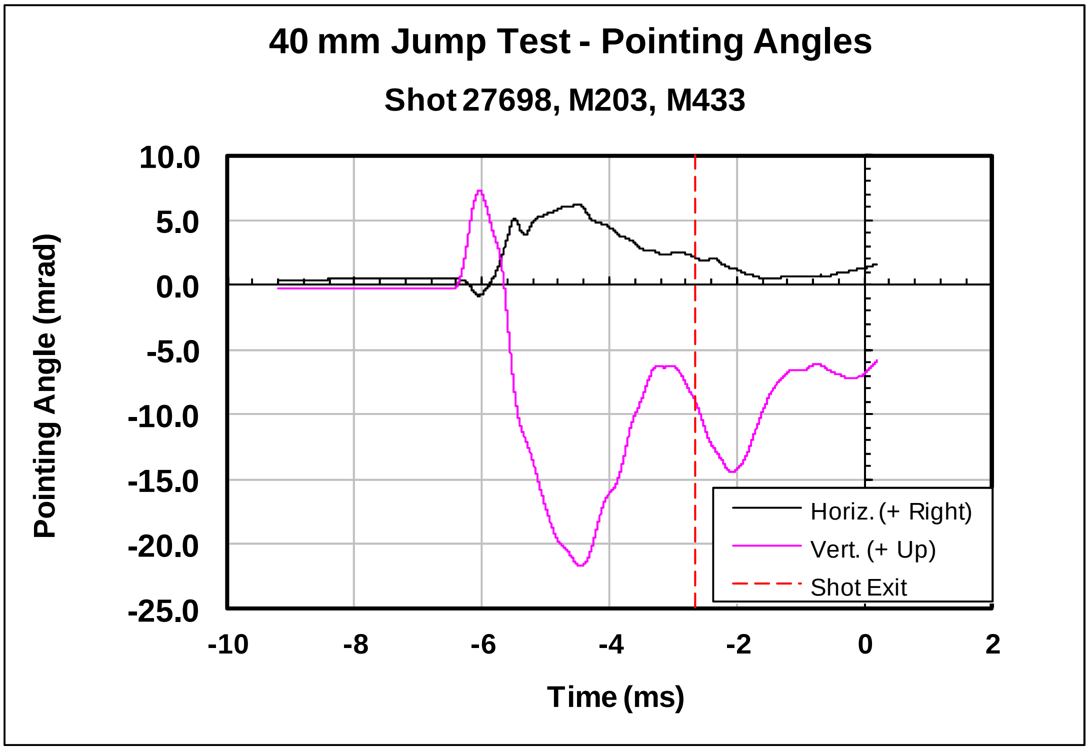

Figure 13. Muzzle-pointing angle.

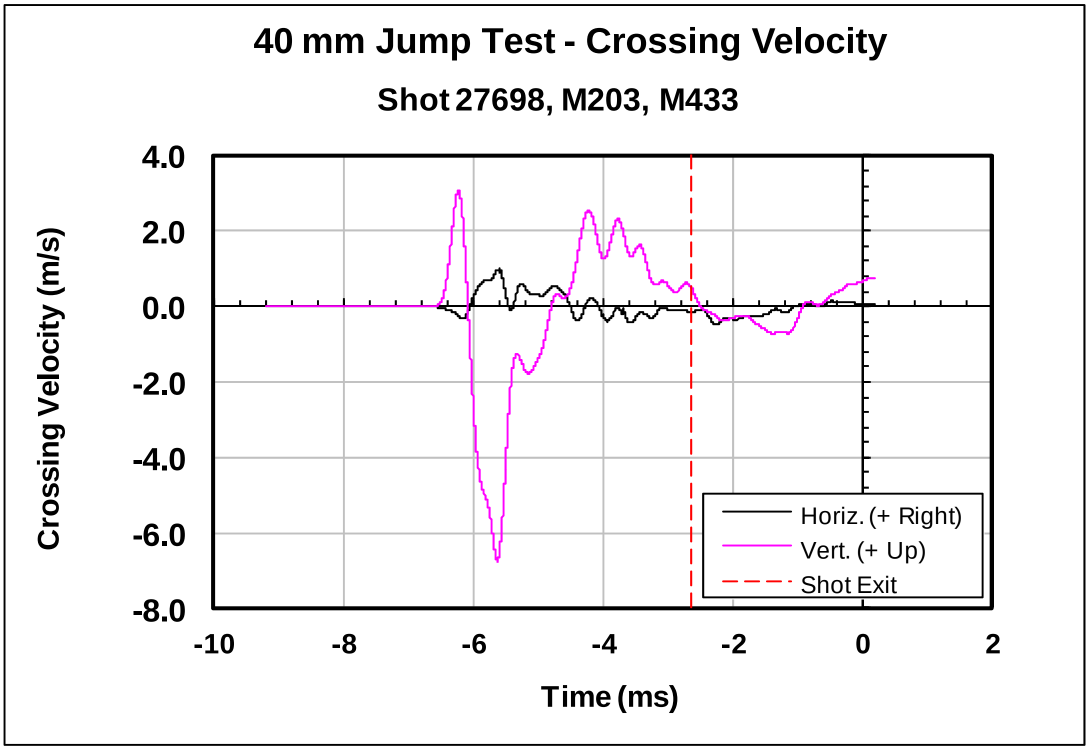

Figure 14. Muzzle-crossing velocity.

5. Conclusions

A new method to process muzzle displacement transducer data has been developed and demonstrated on 5.56 and 40 mm weapon systems. The method allows much more flexibility in the placement of the measurement probes in a test fixture with no loss in measurement fidelity. The method also allows measurements to be taken with as few as two probes per axial measurement location, whereas previously used techniques required four probes.

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